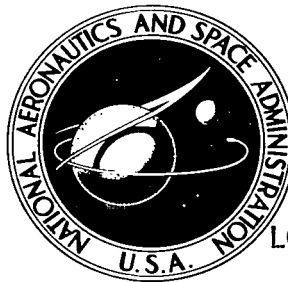


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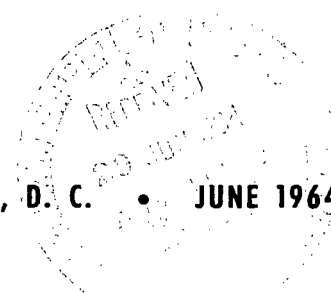
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A MEDIUM-DATA-RATE DIGITAL TELEMETRY SYSTEM

*by Marjorie R. Townsend, Paul M. Feinberg,
and John G. Lesko, Jr.*

*Goddard Space Flight Center
Greenbelt, Md.*

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SUMMARY

Earth-orbiting satellites require on-board data storage. A suitable medium-data-rate digital telemetry system with 10^7 -bit storage is described. Since this storage is provided by a tape recorder, a unique technique for wow and flutter compensation has been developed. Hardware applicable to the radiation experiments on the Tiros and Nimbus meteorological satellites has been built and is currently being tested.

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INTRODUCTION

In addition to television cameras for taking pictures of the earth's cloud cover, the Tiros series of meteorological satellites carries a radiation experiment.[†] The Nimbus series will carry a similar experiment. The earth's temperature is produced by self-emitted radiation and reflected solar radiation. Present medium resolution radiometers filter the combined radiations into five spectral regions. Their geometry is such that the signal has a $(\sin x)/x$ response, the first null occurring at 8 cps for Tiros and at 16 cps for Nimbus. The sampling rate required to reproduce this signal should therefore be greater than twice the maximum frequency response. In this system, each of the five radiometer channels is sampled $33\frac{1}{3}$ times per second.

DATA STORAGE

In a circular earth orbit, data storage on board the satellite is a difficult problem. The most efficient storage system is a tape recorder. In the old FM telemetry system, the limiting factor in terms of signal-to-noise ratio was its wow and flutter. This limit was about 27 db. In the present system, where the data is digitized before it is recorded, it is anticipated that 40 db can be achieved; the limit will then be due to the radiometer itself. Error analyses, not theoretical but practical, which have been run in the laboratory show that the bit-error probability due to the transmission link will be less than 0.1×10^{-7} . This can be achieved even on a recorder having the equivalent of 2 months' operation in orbit.

A brief description of the digital storage system is in order. The tape recorder can store 10^7 bits of data, adequate for an orbit greater than 100 minutes. It measures 6 by 8 by 6-1/2 in., weighs 10-1/2 lb, and uses less than 2 watts in the record mode and about 12 watts in the playback mode. The two-speed recorder (0.45 ips and 11.7 ips) contains up to 250 ft of lubricated

*This report supersedes Goddard Space Flight Center document X-650-63-194, September 1963.

[†]Davis, J.F., Hanel, R. A., et al., "Telemetry Infrared Data from the Tiros Meteorological Satellites," NASA Technical Note D-1293, June 1962.

1/4-in. tape, in a continuous-loop cartridge driven across an 8-track staggered digital record-playback head. Saturation recording is used, the direction of the flux alternating for "ones" and "zeroes", with the bits conservatively packed at 500 per in.

Eight record and eight playback amplifiers can require a considerable volume. In addition, head-lead length should be kept to a minimum to reduce noise pickup. This, then, seemed to be a critical area in which microelectronics could provide a considerable advantage. The result of a contract with CBS Laboratories to develop suitable amplifiers is a package 4 by 1.359 by 1 in. (Figure 1) containing ten record and ten playback amplifiers (two spares) which can be mounted directly on top of the tape recorder, accomplishing the triple purpose of minimizing weight, size, and head-lead length. Each head, which has a nominal impedance of 22 ohms, requires 3.5 ma of current. By deriving this from a constant current source, the power requirement is 10 mw per track during the record cycle.

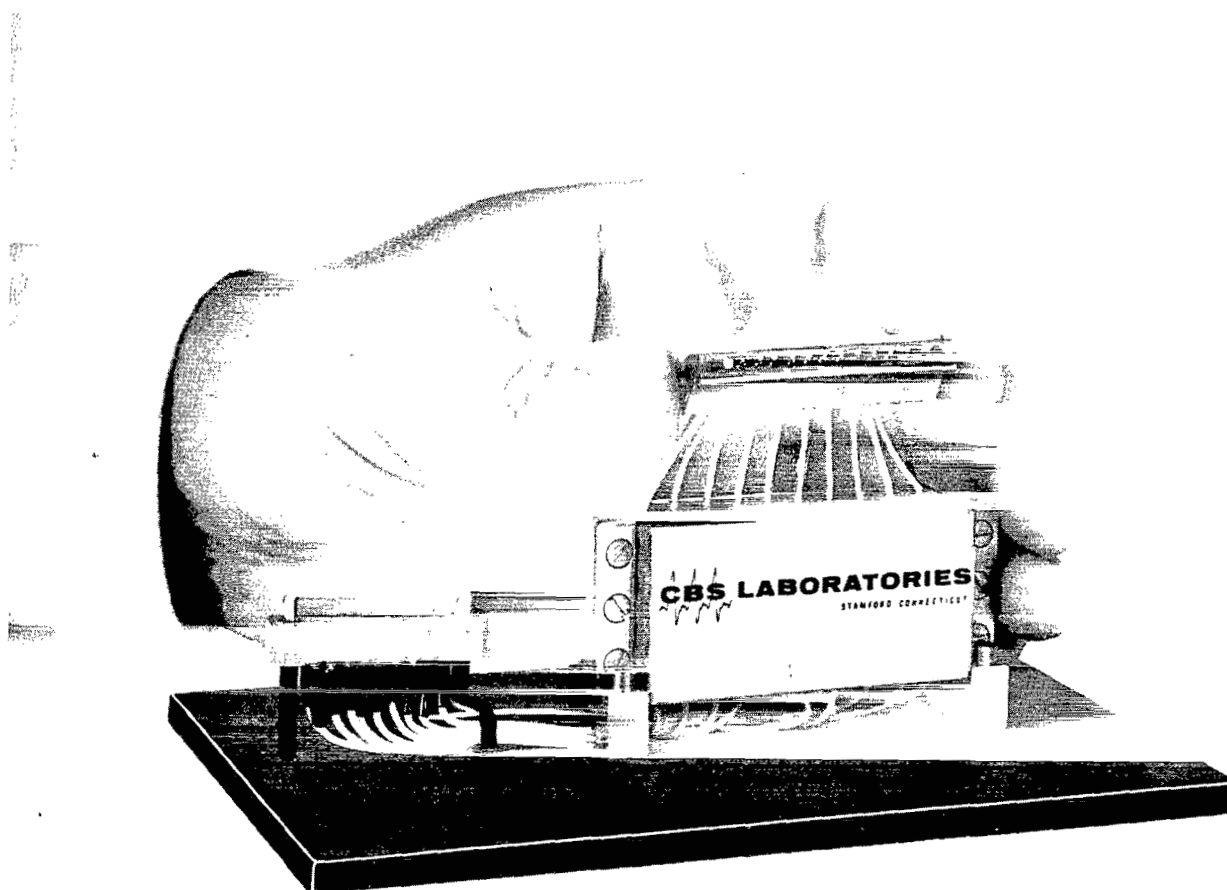


Figure 1—Amplifier package.

SYSTEM DESIGN

The digital electronics package, which weighs about 8 lb, requires 1.5 watts in the record mode and 7.2 watts in the playback mode. This latter figure includes the power used by the transmitter. The total system power is 3.5 watts in record and about 20 watts for the 4 minute playback cycle. The way in which the data and synchronization signals are handled will be considered next. An eight track tape recorder lends itself well to a 7 bit signal recorded in parallel across the tape, the eighth track being used for a clock signal. Seven-bit digital conversion will provide an accuracy of 1 part in 128. The clock track, one of the middle tracks, will be recorded 90 degrees out of phase with the signals on the other seven tracks, so that its edges can be used to trigger the readout in the center of the other data bits.

The record rate chosen was 200 bits per sec on each of the eight tracks in nonreturn-to-zero (NRZ) format, each bit lasting 5 msec. The format (Figure 2) as the signals go on tape is as follows: Frame sync, a signal composed of all "ones", is recorded laterally across the tape. This is followed by the 7 bit output of the analog-to-digital converter. The analog signal from the first of the five radiometer channels, varying between 0 and -6.4 volts, is converted with an accuracy of 1 part in 128. Similarly, the remaining four radiometer channels are converted sequentially to digital form and the resulting bits become words 3 through 6.

The seventh word will contain timing data for Nimbus or a subcommutated channel for Tiros. Coherent with the sampling rate, the Minitrack time code is generated in the Nimbus clock and presented to this system in NRZ format. This information is updated every second, each of its 100 sequential bits lasting 10 msec. Of these 100 bits, only 36 represent timing data. Hundreds of days, tens of days, units of days, tens of hours, units of hours, ten of minutes, units of minutes, tens of seconds, and units of seconds are each indicated by 4 bits. The remaining 64 bits are for synchronization and station identification data. During the 60 msec frame period, 6 of the Minitrack bits will be stored in a shift register. At the proper time for recording the timing word, a "zero" is added, and this plus the 6 Minitrack bits are recorded on tape. Obviously, the 6 bits do not maintain any specific pattern, but they can be unscrambled in a suitable demodulator.

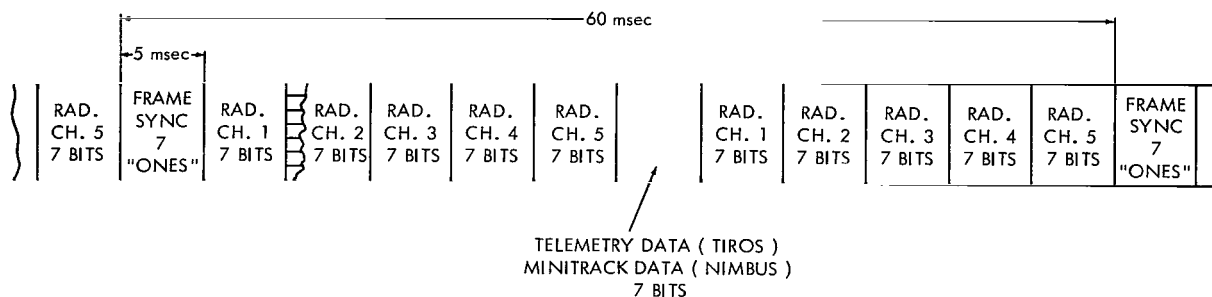


Figure 2—Nimbus and Tiros digital main frame telemetry format.

In the Tiros system, the seventh word is reserved for housekeeping data and a low-data-rate experiment. With a data input channel in this slot every other frame, a piggyback experiment can be sampled 8 times per sec. Alternating with this is subframe sync, the temperature of the radiometer baseplate which is required for accurate data reduction, the temperature and pressure inside the digital tape recorder, and a signal which correlates the radiation data with the TV pictures of the earth's cloud cover.

Words 8 through 12 are the next samples of the five radiometer channels in the same order as words 2 through 6. Thus, each radiometer channel is sampled once every 30 msec. This constitutes the frame, which is repeated over and over for the length of the orbit. The storage capability of the recorder is about 2 hours. Logic will prevent all "ones" from occurring at any time other than frame sync; i.e., 7 data "ones" (127) will never occur.

The Nimbus system block diagram in Figure 3 will help to clarify the system description. The frame format gating network selects 7 "ones" for frame sync, 7 binary bits in parallel from

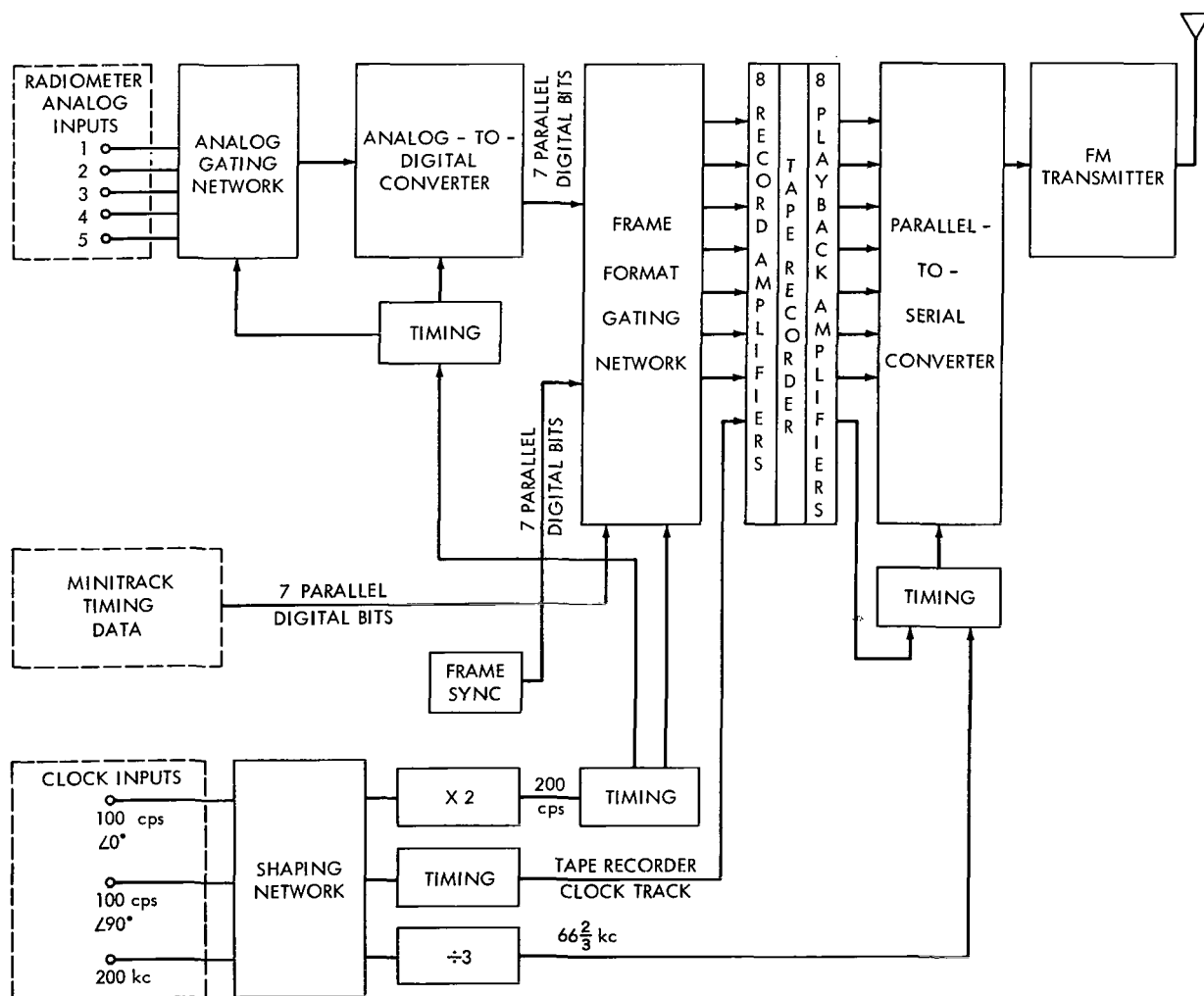


Figure 3—Nimbus medium resolution infrared-pulse code modulation (MRIR-PCM) system.

the analog-to-digital converter whose input is determined by the analog gating network, or the "zero" and 6 bits from the Minitrack storage shift register. The selected 7 pulses, each 5 msec long, either "ones" or "zeros," are applied to seven record amplifiers and recorded on the tape. On the clock track is recorded a 100-cps square wave, equivalent to alternating "ones" and "zeroes" at the 200 bit per sec rate. The change of state of these pulses is delayed by 2.5 msec (half a pulsewidth) in relation to that on the other seven tracks. The purpose of this, as described before, is to use the edges of the clock pulses to sample the data at the optimum time in the middle of the pulse. Figure 4 illustrates the similarities and differences between the Tiros and Nimbus systems. Feinberg gives a detailed description of the system design.*

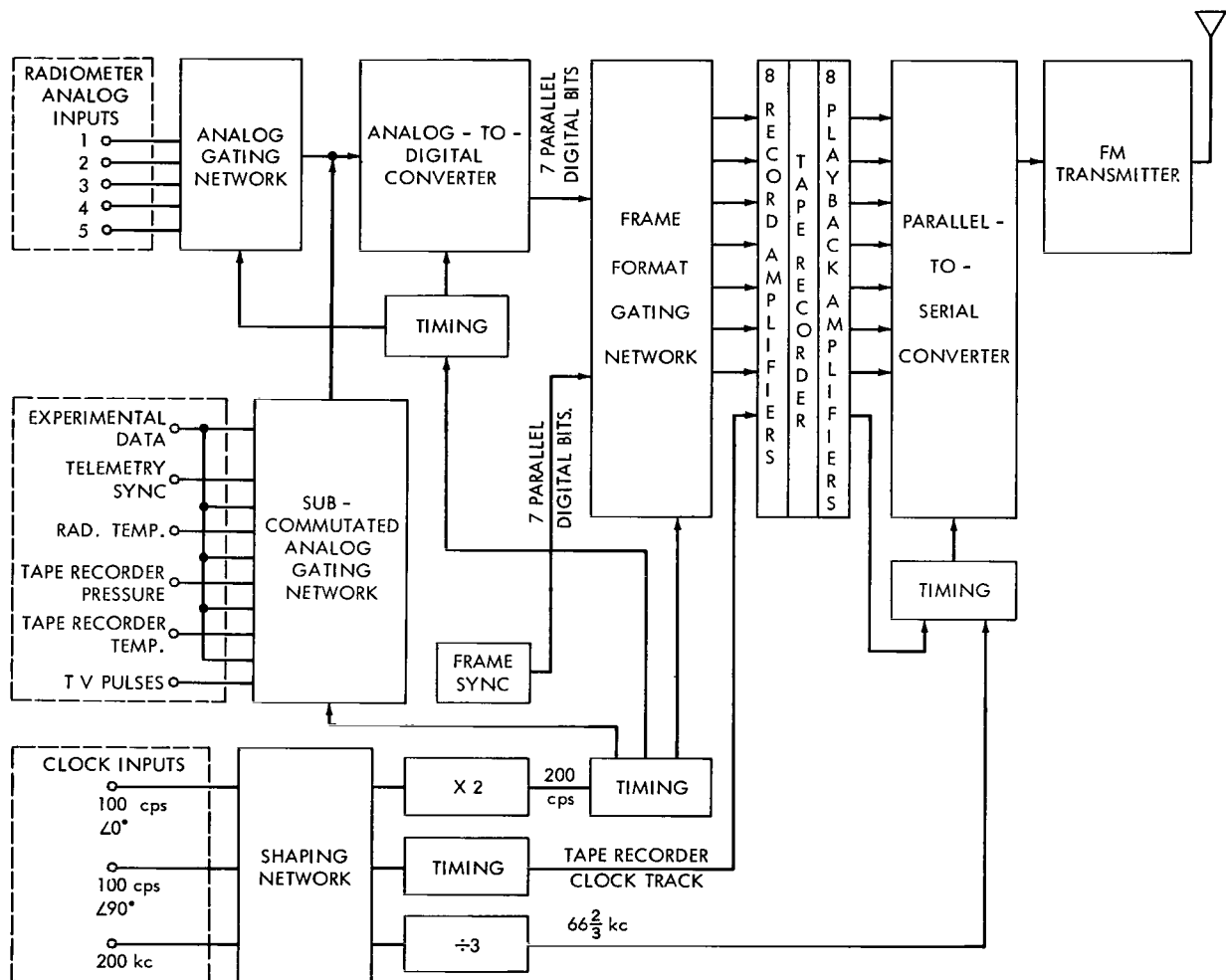


Figure 4—Tiros MRIR-PCM system.

*Feinberg, P. M., "The MRIR-PCM Telemetry System - A Practical Example of Microelectronic Logic Design," NASA Technical Note, to be published.

DATA READOUT AND ACQUISITION

After each orbit which brings the satellite within range, it is interrogated as it passes over the data acquisition station. When the tape recorder is commanded into playback mode, it plays back the stored radiation data at 11.7 ips (a speedup ratio of 26:1) in about 4-1/2 min. The record rate is 200 bits per sec, but the playback rate becomes 5200 bits per sec. This 5.2 kc playback rate varies because of the wow and flutter inherent in the tape recorder. Several techniques are possible for reading out the data from the tape and converting it to serial form for transmission. A discriminator on the output of the clocking track may provide a voltage to control a voltage-controlled oscillator for clocking the parallel-to-serial converter at the output of the tape recorder. However, this would provide a varying transmission rate which would be difficult to synchronize on the ground, so a different technique has been chosen.

Pulses developed from the clock track will trigger the readout of the other seven parallel tracks into storage flip-flops of a parallel-to-serial converter as described above. At this point the format of the frame is completed. A "one" for word sync is added to the beginning of each word in the parallel-to-serial converter as the data is strobed out of the storage flip-flops. A stable frequency from the Nimbus clock (66-2/3 kc), or from a crystal-controlled oscillator for Tiros, is used for strobing these flip-flops so that the transmitted bit rate will be very stable. If no new data is in the storage flip-flops after one strobe is completed, the transmitter will transmit "zeroes" until new data is available. This will happen because the time required to strobe and transmit the seven tracks plus the added "one" will be less than the 5/26 msec, 192 μ sec, between words on the tape. Logic will prevent reading out of the tape while the output register is shifting. This system is designed to guarantee at least one "zero" to prevent the possible occurrence of eight "ones" in a row at a time other than frame sync, and will average about four (4.82) "zeroes" or twelve (12.82) bits per word. This also guarantees a minimum bit rate of 5000 bits per sec. Thus, the transmitted serial train of NRZ pulses contains words of varying length (9 to 15 bits per word) to compensate for the changes in speed of the tape recorder and any

variations in the recording rate. The cost of keeping the transmitted bit rate stable is the need for a 50 percent wider video bandwidth. However, the advantage of the stable transmitted frequency and much less complex spacecraft system make the trade-off worthwhile.

The serial train of pulses thus created frequency-shift-keys a 1.75 watt FM transmitter. Because of the system design, the frequency can vary only between 5000 bits and 66-2/3 kilobits per sec. The deviation selected was ± 25 kc, providing a minimum modulation index of 0.8. Table 1 gives the parameters for a 600 mi. orbit. The results

Table 1
Transmission Data

Datum	Value
Range at horizon	2270 st. mi.
Orbital altitude	600 st. mi.
Path attenuation at horizon	147 db
Path attenuation at zenith	135 db
Satellite antenna gain	-3 db
Ground antenna (85 ft dish) gain	29 db
Antenna temperature	290° K
Cabling losses	-2 db
Transmitter frequency	136 Mc
Transmitter power	1.75 watts
Receiver bandwidth	100 kc
Receiver noise figure	5 db
Signal-to-noise ratio at horizon	28 db
Signal-to-noise ratio at zenith	40 db

show a signal-to-noise ratio into the bit synchronizer of 28 db at the horizon, with 40 db when the satellite is at its zenith point. The use of the 60 ft dish for Tiros reduces these figures by 3 db if the same frequency is used, but the safety factor is adequate.

GROUND DATA PROCESSING SYSTEM

After demodulation by the receivers (Figure 5) the digital signal, still in serial form, is recorded at the ground station on an instrumentation tape recorder. Simultaneously, it is presented to a bit synchronizer whose output is recorded on another track of the same instrumentation tape recorder. A demodulator and digital-to-analog converters are used at the data acquisition station to judge the overall quality of the satellite data. Full-scale data processing must be handled by a computer because of the copious quantities of data.

Figure 6 illustrates the operation of the ground-station complex. After presentation to the bit synchronizer, the serial train of bits is converted to parallel format in an 8 bit shift register where a search is made for the unique frame sync word. When this is detected, a second search begins for the word sync bit which is used to direct the parallel output of the input shift register to the proper digital-to-analog converter flip-flop storage network. Eight bits are counted out for

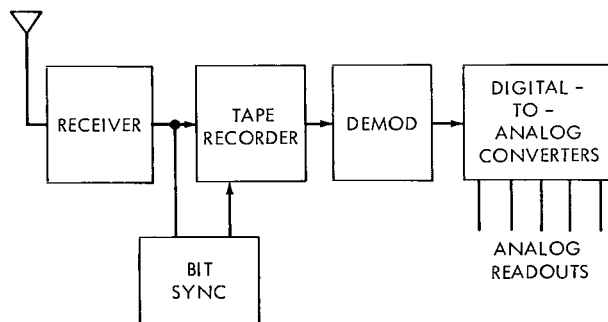


Figure 5—Data acquisition station diagram.

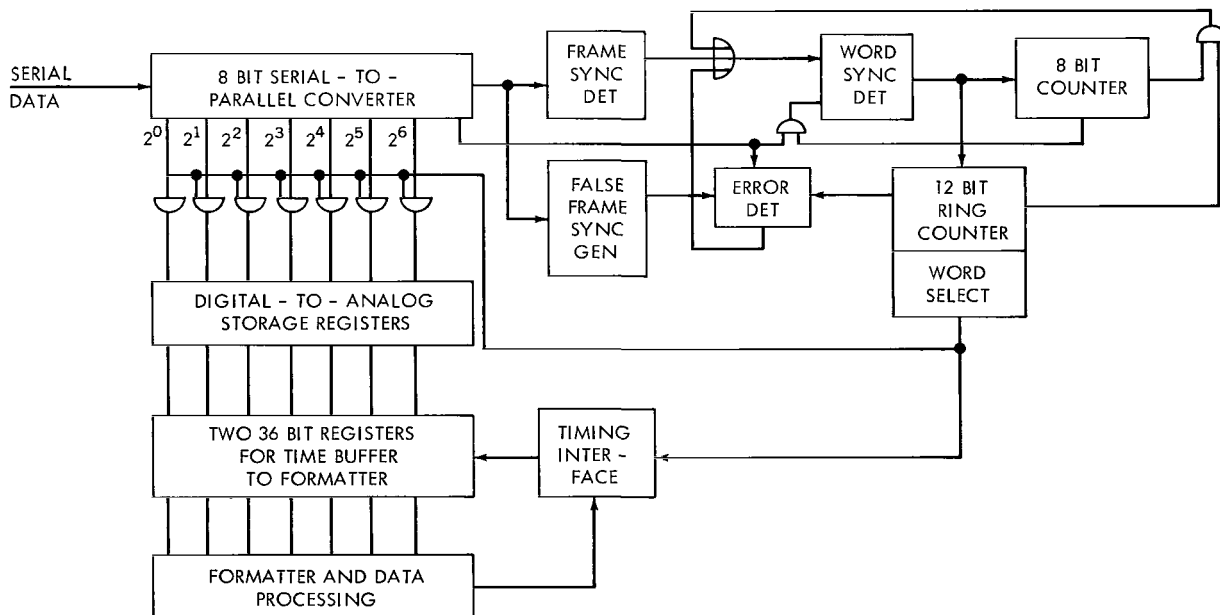


Figure 6—Simplified ground station diagram.

each word, if the "zero" bits which follow it are ignored, and twelve words are counted out between frames. This procedure continues through the whole twelve word frame, after which the search for frame sync begins again.

If frame sync should fail to appear within a selected time tolerance, a false frame sync is generated in the Tiros ground stations, since the loss of data words could mean a loss in time correlation and thus an error in determining the correct orbital geometry. To provide a surer selection of true frame sync, three frame syncs must be detected, without error, before a frame sync error is locked out. Three errors in one frame will put the system back into the search mode again, looking for true frame sync. An error is defined as finding that the ninth bit after word sync is a "one" instead of a "zero," or that frame sync does not occur within the proper time interval.

An output signal will occur after 64 false frame syncs to flag the occurrence of the splice or serious losses of data. Almost that many can be expected each orbit at the tape splice. Sixty-four frames are equivalent to 3.84 sec of data, a small percentage from a 90 minute orbit, but important in terms of maintaining time.

The individual words can be directed to digital-to-analog converters, so that the signal levels for each channel may be analyzed by hand, or they may be directed to a formatter where they are combined into standard 36 bit IBM words and transferred to a digital tape which can be handled automatically by a computer. The format will be the same as that now used for the Tiros radiation experiment data. However, the housekeeping data which appear on the subcommutated channel will appear periodically as a special word on the tape and will be decommutated by the computer. With this data the calibration of the radiometer data can be adjusted automatically to conform to the changing satellite temperature. The error-output signal described above will generate a special code word to tell the computer about the occurrence of unacceptable data.

For Nimbus, absolute time in the form of the Minitrack time code will appear on the computer tape as a single word, which is updated every real-time second. There will be about 33 data words between each timing word, which will be flagged to the computer by a special code word.

The normal five channel data will be handled by shifting each 7 bit data word in parallel into a 36 bit shift register. After the register has five words or 35 bits, a "one" is added in the 36th bit and the IBM-formatted word is shifted out in groups of 6 bits. While this shifting operation is occurring, the data words will be stored in a second identical 36 bit shift register which alternates with the first in accepting data and shifting them into a buffer. From the buffer the data are formatted onto the digital tape.

HARDWARE

The hardware (Figure 7) for this telemetry system has been designed and built with the Series 51 integrated circuits developed by Texas Instruments. Flip-flops and different types of

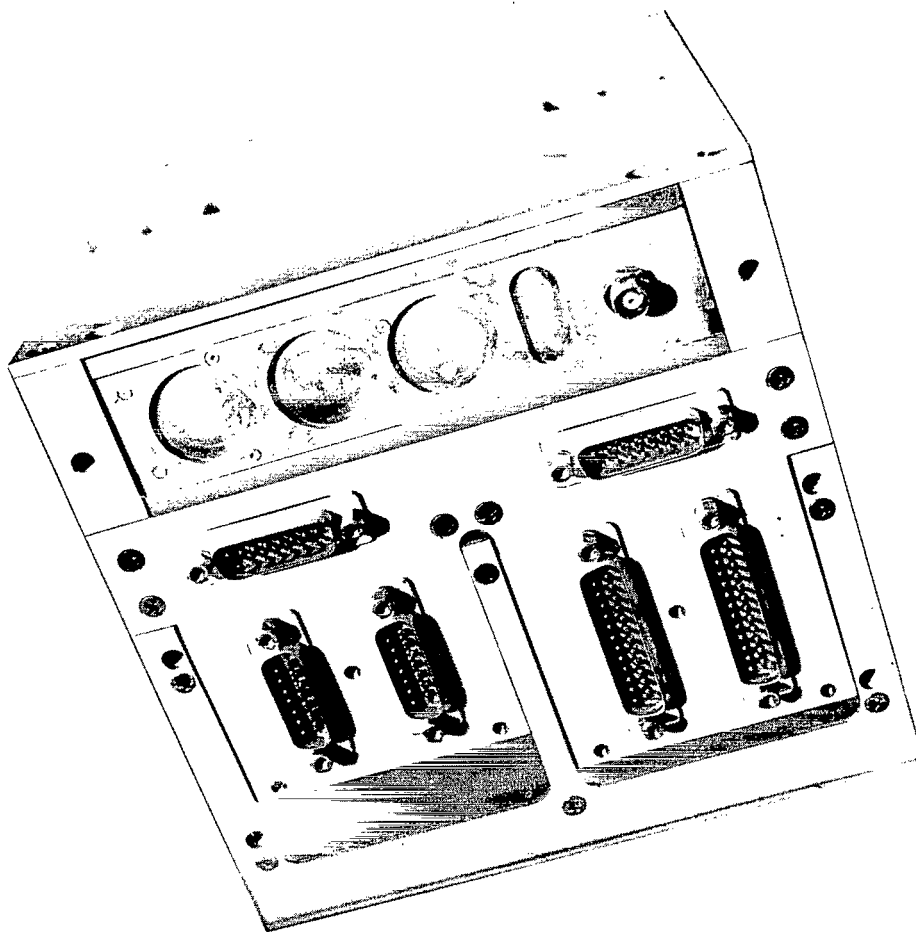


Figure 7—Telemetry system.

gates are fabricated in tiny individual modules from which the logic circuitry may be constructed. Using this type of circuitry should represent a significant advance in the reliability achieved in such a system. The record and playback amplifiers previously described and the logic for the analog-to-digital converter are being built in microelectronic form. Analog portions of the analog-to-digital converter and the analog gates are constructed from standard discrete components.

The converter (Figure 8) encodes using the successive approximation technique; it completes the encoding process in $320 \mu\text{sec}$. The total conversion error over a temperature range of 0° to 60°C is $\pm 10 \text{ mv}$. The total accuracy is $\pm 25 \text{ mv}$, half the least significant bit of 50 mv . The converter is designed so that a simple change would make it an 8 bit converter; its inherent accuracy provides that capability. The power required to operate the converter is 170 mw ; of this, only 12 mw is required for the micropower logic circuitry, the remaining power being used for the conventional solid-state circuits.

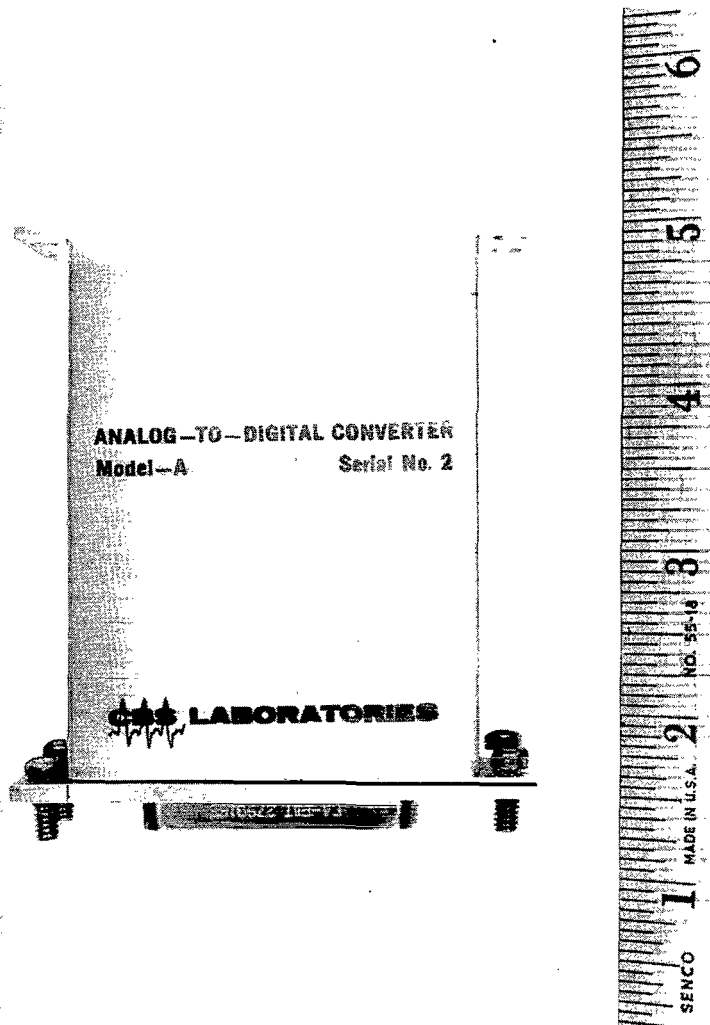


Figure 8—Analog-to-digital converter.

CONCLUSION

This digital method of treating the data from the medium resolution radiation experiments planned for future Tiros and Nimbus satellites is expected to result in a fivefold improvement in accuracy over the FM analog system previously used. The integrated circuits are versatile, reliable, and ideally suited for present and future aerospace requirements.

(Manuscript received October 29, 1963)

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